Scientific highlights and status of the MAGIC Telescope

Outline:
- Introduction
- Galactic observations
- Extragalactic observations
- Dark matter searches
- MAGIC-II
The MAGIC Collaboration

Collaboration: ~ 150 Physicists, 23 Institutes, 12 Countries:
Instituto de Astrofísica de Andalucía, IFAE, UAB, Barcelona, UBarcelona,
DESY Zeuthen, Instituto de Astrofísica Canarias, INAF Rome,
Croatian MAGIC consortium, University C. Davis, University Dortmund,
Institut de Ciencies de l’Espai, University Lodz, UCM Madrid, MPI Munich, INFN/
University Padua, INFN/ University Siena/Pisa, Institute for Nuclear
Research Sofia, Tuorla Observatory,
Yerevan Institute,
INFN/University Udine,
University Würzburg,
ETH Zürich

Goal: Achieve the lowest energy threshold in the world
Close unexplored gap between space and
ground-based gamma telescopes
The MAGIC telescope

La Palma, IAC
28° North, 18° West

~2240 m asl
The MAGIC telescope

- Largest single dish CT:
  17 m Ø mirror dish (241 m²)
- Camera with 577 enhanced QE PMT’s, 3.5° FoV
- Ultra-light carbon fibre frame:
  - Fast repositioning for GRBs: average < 40 s
- Enhanced duty cycle (by 50%) thanks to moonlight & twilight observations
- Performance:
  - Low energy threshold:
    - Std: 55 GeV
    - Sumtrigger: 25 GeV
  - Sensitivity: 1.6% Crab/50h
  - Angular resolution: ~ 0.1°
  - Energy resolution: 20-30%

In regular observation mode since fall 2004
Basic fact: $\gamma$-rays absorbed in atmosphere

Satellites
- Direct detection
- Small background
- Small Effective Area $\sim 1\text{m}^2$

Ground Detectors
- Indirect detection
- Huge Effective Area $\sim 10^6\text{m}^2$
- Enormous hadronic background
MAGIC Physics Targets

Galactic
- Pulsars/PWN
- SNRs
- Binary systems

Extragalactic
- AGN
- Radio galaxy
- GRBs

Fundamental Physics
- Dark matter
- Origin of cosmic rays
- Space time
The $\gamma$–ray sky

- EGRET gave a nice crowded picture of energies up to 10 GeV.

- Ground-based experiments show very few sources In spite of having much better sensitivity!

- Situation dramatically changed thanks to the new generation of CTs

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Highlights in MAGIC galactic observations

4 discoveries, 6 more detected, U.L on many others
Pulsars visible in VHE $\gamma$-rays?

- Maximum of emission at hard X- and $\gamma$-ray
- Spectra are very different above 1 GeV
  
  *High energy spectral cutoffs*

- Observational challenge since 20 years
- Instrument with sensitivity well below 100 GeV needed

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A new trigger concept

24 Clusters of 18 pixels in a ring area

Add analog signals from a cluster & discriminate on summed signal

Problem: Large amplitude from Afterpulses
  - Solved by clipping signal

Built in summer 2007

MAGIC SumTrigger

Clipped at 6-8 PhE
A new trigger concept

Improvements

- Size distribution peak shifts to lower energies
- Higher collection area at low E
- Sum & std trigger data taken in parallel
- Trigger threshold decreased in a factor ~2

Low trigger threshold of 25 GeV:

a break-through for ground-based γ-ray astronomy

Trigger threshold decreased in a factor ~2

Improvement in detection efficiency @ 20 GeV: factor 8
Detection of the Crab pulsar above 25 GeV

Observations with new trigger
- Oct.07 to Feb.08: 22.3 h

Clear detection: $6.4 \sigma$
Pulses in phase with EGRET

P1 clearly visible
at 25 GeV
→First Surprise

Pulsed emission
still visible $> 60$
GeV!
$P_2$ became dominant

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Total spectrum & cutoff

$E_0 = 17.7 \pm 2.8_{\text{stat}} \pm 5.0_{\text{syst}} \text{GeV for } \beta = 1$ (exponential)

$E_0 = 23.2 \pm 2.9_{\text{stat}} \pm 6.6_{\text{syst}} \text{GeV for } \beta = 2$ (super-exponential)
Our superexponential cutoff:

$$23.2 \text{ GeV} \pm 2.9_{\text{stat}} \text{ GeV} \pm 6.6_{\text{syst}} \text{ GeV}$$

We can calculate the absorption of gamma-rays in the magnetic field

$$\varepsilon_{\text{max}} = 0.4 \sqrt{\frac{P}{R_0}} \max \left\{ 1, \frac{0.1 B_{\text{crit}}}{B_0} \left( \frac{r}{R_0} \right)^3 \right\} \text{GeV}$$

Baring et al., 2001

From which we can put a lower limit on the distance of the emitting region:

$$6.2 \pm 0.2_{\text{stat}} \pm 0.4_{\text{syst}} \text{ neutron star radii}$$

The high location of the emission region excludes the classical polar cap model (emission distance < 1 stellar radius) and challenges the slot gap model
SNR IC 443 (MAGIC J0616+225)

- Asymmetric shell-type SNR, 45’ diameter (distance ~1.5 kpc)
  - Unidentified EGRET source inside
  - Only upper limits in VHE $\gamma$-rays

- Discovered by MAGIC in 2007 (recently confirmed by Veritas)

Radio:

- Shows Maser emission

SNR IC 443 (MAGIC J0616+225)

- X-ray
- EGRET 12CO emission
- Point-like source

Acceleration process in is currently unknown: hadronic origin of VHE emission?

Radio data

F(E>100 GeV) ~ 6.5% Crab

$\Gamma = 3.1 \pm 0.3 \pm 0.2$
LSI+61 303

- High mass x-ray binary system
  - Be star (18 $M_\odot$) &
  - Unknown compact object: neutron star, BH?
- Discovered by MAGIC in 2005/06
- Visible only at some orbital phases

First time a periodically variable VHE emitter was seen
Spectral index remains during different phases, even if flux changes by factor of 3

\[ \Gamma = 2.6 \pm 0.2_{\text{stat}} \pm 0.2_{\text{sys}} \]
LSI+63 303: MW campaigns

Radio/VHE?

- MW campaign Oct/Nov 06 in Radio, X-rays & VHE

X-ray/VHE?

- New MW campaign in 2007 with XMM, Newton and Swift
  - Simultaneous data show evidence for X-ray/VHE correlation (r=0.81)
Cygnus X-1

- One of the brightest X-ray sources in the sky
  - BH turning around an O-type star
- Observed 40h in 2006 with MAGIC in 26 nights
  - No steady $\gamma$-ray signal: U.L. below $\sim$1\% Crab flux
  - Detected a flare on 24$^{th}$ Sept. 2006 at 4.1 $\sigma$ (post trial)
VHE flare coincident with X-ray flares seen by Swift/BAT, RXTE/ASM and Integral

TeV excess observed at rising edge of first hard X-ray peak

Hard X-rays and VHE $\gamma$-rays could be produced at different regions of the jet ➔ shift between TeV- and X-ray peak
Wolf-Rayet binary systems

- Binary systems containing a WR star:
  - colliding winds (up to 5000 km/s) could produce $\gamma$-rays via leptonic or hadronic processes (e.g. Reimer et al. 2006)

- MAGIC observed two WR binary systems:
  - **WR146**: WC6+O8 colliding wind binary system in the field of view of TeV J2032+4130; combined observation, T=30h
  - **WR147**: WN8(h) plus a

  Reimer’s model for WR147 assumes parameters still unknown ➔ Model can’t be rule out, but the phase can be constrained (period is 1500yrs!)
Highlights in MAGIC extragalactic observations

M87 (z=0.0043)  Mrk421 (z=0.031)  Mrk501 (z=0.034)  1ES2344 (z=0.044)  Mrk180 (z=0.045)

1ES1959 (z=0.047)  BL-Lacertae (z=0.069)  1ES1218 (z=0.18)  PG 1553+113 (z>0.25)

MAGIC discovery  MAGIC discovery  MAGIC discovery  MAGIC codiscovery

MAGIC J0223  3C279 (z=0.536)  S5 0716 (z=0.31)  1ES1011 (z=0.212)
Optical triggers ➔ new VHE sources

- Regular optical monitoring of candidate sources by KVA telescope (close to MAGIC site)

Mkn 180

z = 0.045

ToO trigger

Mkn 180, z = 0.045


March 2006

MAGIC

12.1 h

S = 5.5 σ

1ES 1011+496

z = 0.212

ToO trigger

1ES 1011+496, z = 0.212


March-May 07

MAGIC

18.7 h

S = 6.2 σ

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After trigger, MAGIC observed 2.6h

- April 28: Swift reports flux about 50% larger than that observed in 2007
- Apr 29: ATel #1500, MAGIC reports 6.8 $\sigma$ discovery Apr 23-25. $F(>400 \text{ GeV}) \approx 25\%$ Crab

- 3rd low-peaked VHE blazar after BL Lac & W comae
- Host galaxy detected: $Z=0.31 +/- 0.08$
- 2nd farthest VHE emitter

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Observations in the vicinity of 3C 66A

- Optical outburst in August 2007 triggered MAGIC observation:
  - from August to December, a total of 54.2 h
- Detection at 5.4 \( \sigma \), \( F(E>150 \text{ GeV}) = 2.2\% \text{ Crab} \)

3C 66B is the most likely identification: 3C 66A excluded with 85% probability

A or B?

- 3C 66A/B: just separated 6’ in the sky
  - 3C 66A blazar with uncertain redshift, \( z=0.32-0.44 \)
  - 3C 66B large FR-I radio galaxy, similar to M87, \( z=0.0215 \)

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The distant quasar 3C 279

- Flat spectrum radio quasar (z=0.54)
- Very bright and strongly variable
  - Brightest EGRET AGN
- MAGIC observations
  - 10 h between Jan.-April 2006
  - clear detection on 23\textsuperscript{rd} Feb. at 6.2 \( \sigma \)
The distant quasar 3C 279

- New observations after optical outburst in Jan. 2007
  ➔ New flare detected

Most distant object ever detected at VH,E during two flares
(Feb. 2006 and Jan. 2007)

Emission harder than expected -> constrains the EBL, universe more transparent to Y-rays than expected

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- γ-rays from the source interact with the EBL in their way to the Earth, producing e+/e- pair.
- For γ-rays, relevant background component is optical/infrared (EBL).
- Different models for EBL: minimum density given by cosmology/star formation.
Implications on Extragalactic Background Light

AGNs & EBL

- Measured spectrum affected by attenuation in the EBL

![](image1)

- Measurement of spectral features permits to constrain EBL models:
  - 3c 279 Power law $\Gamma = -4.11 +/- 0.68$ ➔ Spectrum sensitive to 0.2 to 2

The Universe appears more transparent at cosmological distances than believed

- Upper limit close to lower limit from galaxy count
M87 giant flare

- Radio galaxy with super massive black hole $\sim 6 \cdot 10^9 \, M_\odot$ at $\sim 16$Mpc
- Jet structure with knots, sometimes brighter than nucleus
- Established VHE $\gamma$-ray emitter: HEGRA, HESS, Veritas & MAGIC
  - Site for TeV emission (core/HST-1)?
- Source of UHECR?
M87 giant flare

MWL campaign Jan-Feb 2008

- Triggered by MAGIC detection on 1st February flare:
  - 9.9σ detection; 8.0σ single night 1st-feb
- Discovered:
  - Fast (day-scale) variability
  - Correlated TeV flare with radio & X-ray emission from the core, while emission from HST-1 knot stayed low
- Origin of the VHE γ-ray emission is most likely the core of the jet

Origin of the VHE γ-ray emission is most likely the core of the jet
Indirect Dark Matter searches

- Standard Cosmological scenario of Cold Dark Matter
- Neutralino (lightest SUSY particle) attractive candidate

\[ \Phi_\gamma (\Omega) \propto \frac{N_\gamma v \sigma}{M^2} \int \rho_{DM}^2 (l) dl(\Omega) \]

\textbf{CDM density:} \( \gamma \)-ray flux \( \sim \rho^2 \) => need region with high \( \rho \)

Where to search?
- Galactic center? obscured by strong VHE source
- Other galaxies, galaxy clusters? expect other VHE
- minihalos, IMBHs, ...? don’t know where they are (yet)
- spheroidal satellite dwarf galaxies? expect to be dim but cleaner signal
Observations of Sph. dwarf galaxies

Need significant increase in sensitivity to come close to model predictions

- **Draco**
  - 8h in 2007 at large zenith angle (37°) => \(E_{th} = 140\text{GeV} \)
  - u.l.: \(\Phi(E>140\text{GeV}) \sim 10^{-11} \ \gamma \text{cm}^{-2}\text{s}^{-1} \) (assuming spectral index -1.5)
  - U.L. depends on expected spectra: different for each mSUGRA model

- **Willman I**
  - 15h in 2008
  - u.l.: \(\Phi(E>100\text{GeV}) \sim 10^{-11} \ \gamma \text{cm}^{-2}\text{s}^{-1} \)
Why stereo?
Stereoscopic provides:
- Better reconstruction of shower direction
- Additional shower param.:  
  - Impact parameter  
  - Shower maximum
- Eliminate ambiguity on shower arrival direction

This means:
- Better hadron rejection
- Better angular resolution
- Better energy resolution
- Enhance the sensitivity over the whole energy range (2-3 better)
MAGIC-II not just a clone

- Improved 1m² mirrors:
  - bigger, lighter
  - 2 technologies: Al, glass

- Improved camera:
  - High efficiency PMTS
    - 1039 x 0.1° pixels
  - Modular Design
    - Cluster of 7 pixels
    - Easy replacement
  - Total FOV = 3.5°

- Improved readout:
  - Uses DominoRing sampler

- Increased trigger area
  - Improved sensitivity for: sky scans, extended sources

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Completed on July 2008
Installed December 2008
MAGIC-II already running!

- First images & inauguration in April 2009
- First stereo events in June
- Since September all data taken with both telescopes

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Conclusions

- MAGIC is producing high quality physics after 4 observation cycles:
  - last year 15 articles published, 2 in Science
- We have discovered new sources (and new populations)
  - 4 new galactic sources + 8 extragalactic, and studied many others in high detail
- Important contributions to the understanding of pulsars, AGN, EBL...
- MAGIC-II just started regular operations
"The story of the MAGIC project is a textbook example of the merging of particle physics and astronomy into the modern field of astroparticle physics"
BACKUP
Best studied: the Crab Nebula

- Crab Nebula spectrum measured with high precision between 60 GeV and 9 TeV
  - Good agreement with other CTs above 400 GeV
- First determination of the IC-peak:
  \[ E = (77 \pm 35) \text{ GeV} \]
- Spectrum well described within SSC model

**Fermi (F. Loparco, Ricap09)**

The GeV - TeV connection:
The Crab Nebula can be used as cross-calibration source → reduce uncertainty in the energy scale of IACTs
LSI+63 303: Is the LC periodic?

- Periodicity test reveals highly significant period
  \[ P = 26.8 \pm 0.2 \text{ days} \]
  - consistent with emission at other wavelengths
Observations in the vicinity of 3C 66A

F(E > 150 GeV) ~ 2.2% Crab ➔ lowest ever detected by MAGIC
(Cannot exclude contribution of 3C 66A at lowest energies)

If 3C66A (unlikely) ➔ distance cannot be z > 0.23 (no > 1 TeV γ-rays, EBL)
Hard spectra possible, but require unusual blazar energetics (L>10^{47} erg s^{-1})
3C279 and the $\gamma$-ray horizon

Test of the transparency of the universe extended to $z = 0.536!$
Fundamental physics

Energy-delayed flare of Mrk501

- Quantification of the delay:
  \[ \Delta t = 0.030 \pm 0.012 \text{ s/GeV} \]
  Probability of no delay: 2.6%

- Possible explanations:
  - Astrophysical: intrinsic source effects
  - Photons at different energies were emitted simultaneously:
    Propagation effect due to Lorentz invariance violation:

\[
c' = c \left[ 1 \pm \frac{\xi}{E_s} \pm \zeta \left( \frac{E}{E_s} \right)^2 \right] \quad \Delta t \approx \frac{\Delta E}{E_s} \frac{L}{c}
\]

- Probing the Planck energy scale